A COMPUTATIONAL MODEL OF THE PREGNANT OCCUPANT: EFFECTS OF RESTRAINT USAGE AND OCCUPANT POSITION ON FETAL INJURY RISK

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ABSTRACT

Automobile crashes are the largest single cause of death for pregnant and the leading cause of traumatic fetal injury mortality in the United States. The purpose of this paper is to present a validated model of a 30 week pregnant occupant and to examine the risk of fetal injury in frontal crashes. The pregnant uterine model was imported into MADYMO 6.0 and included in the 5th percentile female human body model using membrane elements to serve as ligaments and facet surfaces for the overlying skin. A simulation matrix of 17 tests was developed to predict fetal outcome and included frontal crash impulses from minor (<24 kph), to moderate (24-48 kph), and severe (>48 kph) crashes for the driver and passenger occupant positions. The test matrix also included various restraint combinations: no restraint, lap belt, 3-point belt, 3-point with airbag, and airbag only. Overall, the highest risk for fetal death was seen in higher speed frontal accidents in the driver position for all restraint conditions. The peak uterine strain was reduced by 26 % to 54 % for the passenger position versus the driver position. This difference was due primarily to driver interaction with the steering wheel. For all impact directions, the maternal injury indices were greatest for the unrestrained occupant. In addition, the possibility of direct fetal brain injury from inertial loading alone appears possible and a component that should be included in further models. The current modeling effort has verified previous experimental findings regarding the importance of proper restraint use for the pregnant occupant.

INTRODUCTION

Automobile crashes are the largest single cause of death for pregnant females [1] and the leading cause of traumatic fetal injury mortality in the United States (US) [22]. Each year, 160 pregnant women are killed in motor-vehicle crashes (MVCs) and an additional 800 to 3200 fetuses are killed when the mother survives [10 & 11] in the US. Unfortunately, fetal injury in motor vehicle crashes is difficult to predict due to the fact that real world crash data is limited and cadaver studies are not feasible.

In the non-pregnant female, the uterus is a muscular organ the size of a lemon located within the abdominal cavity. As the fetus grows during pregnancy, the abdomen stretches to the size of a watermelon. The internal volume increases from 0.005 L to 5 L and as much as 10 L [20]. The uterine wall is uniform prior to delivery, with a thickness of about 1 cm. The uterosacral and round ligaments extend from the uterus to the pelvis and act to support the uterus. The interior of the uterus contains the fetus, which is surrounded by amniotic fluid and the placenta (Figure 1). The placenta is a vascular organ that acts as a permeable membrane that exchanges oxygen, nutrients, and waste products between the mother and fetus via the umbilical cord. It is a flat, roughly circular structure 2 cm thick in the center. Most placentas, as many as 95%, are in the upper half of the uterus [6]. Testing by Fried [6] showed that 31% of the placentas were wholly or partly fundal (at the top of the uterus) and by the 3rd trimester, 40% of the placentas were fundal. The cephalic presentation, in which the fetus is in a head down position, comprises about 75% of pregnancies [6].

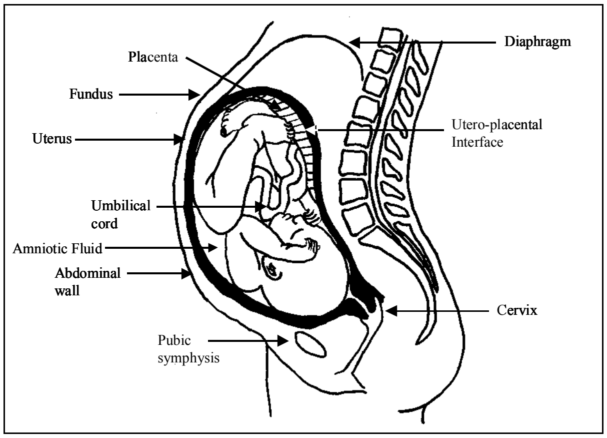


Figure 1. Anatomy of a 40-week pregnant woman (ligaments not shown).

In an effort to reduce the risk of injury to pregnant occupants in car crashes, research was performed on pregnant primates that illustrated the effectiveness of restraint systems in preventing fetal and maternal death [9]. More recently, a pregnant anthropometric test dummy (ATD) has been developed at the University of Michigan Transportation Research Institute [20]. The Maternal Anthropomorphic Measurement Apparatus Version 2B (MAMA-2B) is a second-generation prototype ATD that is a retrofit Hybrid III small female dummy. One of the primary limitations of the pregnant dummy is the lack of injury criteria for the fetus. The MAMA-2B was designed to measure anterior and posterior pressure in the fluid-filled abdomen insert as well as the strain on the perimeter of the insert. However, only the anterior pressure measurements were repeatable [20]. Therefore, it would be beneficial to have an injury criterion for the pregnant dummy that utilizes currently established ATD measurement methods. One leading example would be to measure overall abdominal compression in a similar manner that used to measure chest compression. For example, this could be done by using a string potentiometer as is done in the chest.

The most common cause of fetal death from motor vehicle accidents is placental abruption, which is the premature separation of the placenta from the uterus [11]. Both the pregnant dummy and the pregnant model presented in this study utilize this injury mechanism to predict fetal outcome [14]. However, due to the difficulties in measuring this mechanism in the pregnant dummy, such as tissue strain and pressure, a computational model is desired that can accurately predict fetal injury risk. Therefore, the purpose of this paper is to present a validated model of the pregnant occupant to examine the risk of fetal injury in frontal crashes for a range of restraint configurations in both driver and passenger occupant positions.

METHODOLOGY

Motor vehicle crashes were simulated using the MADYMO (TNO, Netherlands) software package. In order to create the pregnant occupant, the finite element model of a pregnant uterus was inserted into the abdomen of a multibody human model (Figure 2) [14, 15, & 17]. The finite element uterine model is designed to represent an occupant in her 30th week of gestation. The abdomen consists of the uterus, placenta, and amniotic fluid. A fetus was not included because the injury mechanisms that predominantly contribute to fetal loss, as described by [20], are independent of the fetus. The uterus is 27 cm long, 18 cm wide, and 1 cm thick. The placenta is located at the fundus of the uterus and is 2 cm thick. The remainder of the interior of the uterus is filled with the amniotic fluid. The human model is a 5th percentile female (5 ft tall, 110 lbs) and the weight of the pregnant occupant model is 135 lbs. The multibody human model provides biofidelic response of an occupant in a motor vehicle crash, while reducing the computational time compared to a full finite element human model. The anthropometry of a pregnant woman was quantified by Klinich [10]. The abdominal contour of the pregnant model closely matches the Klinich data.

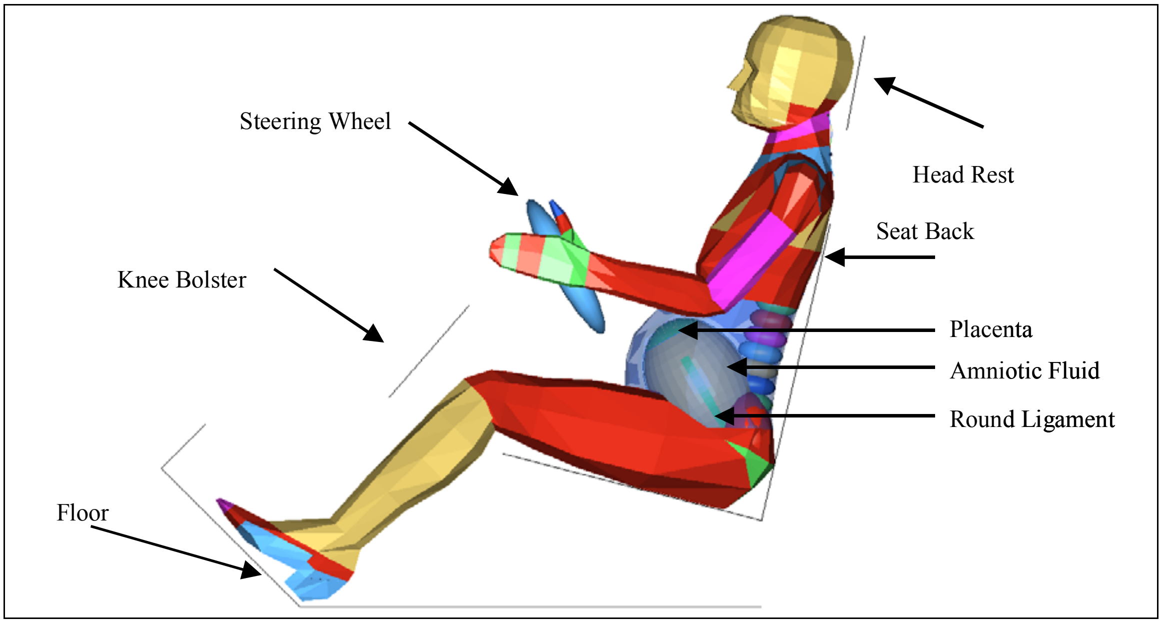


Figure 2. Pregnant occupant in the driver-side interior.

The uterine model is supported to the human model by the uterosacral and round ligaments, as well as the cervix. The bottom four nodes of each ligament are constrained to move with the pelvis for both translation and rotation. The uterine model is also surrounded by fat to represent the boundary conditions involving the spine, abdominal organs, and the pelvis. All uterine bodies were modeled as linear elastic solids. Although the uterus and placenta are considered visco-elastic and anisotropic [2, 13, & 19], sufficient data was not available to accurately apply these material types. The amniotic fluid was modeled as a solid because MADYMO does not utilize fluid elements at the time of model development.

Tension tests on human uterus tissue have been reported by Pearlman [18], Pearsall [19], and Wood [23]. The Young's modulus ranged from 20.3 kPa to 1379 kPa, with an average of 566 kPa. The Poisson's ratio is set to 0.40 since the uterus is a muscular organ and the density is 1052 kg/m^3. Pearlman [18] reported the results of five tension tests on placental specimen. The average modulus was 33 kPa, with a high of 63 kPa. Testing was not taken to failure. The highest modulus is used in the pregnant model because it is expected that the placenta is stiffer than the fat. The Poisson's ratio is assumed to be 0.45 because it is muscular tissue (ν=0.40) engorged with blood (ν=0.50). The density of the placenta is 995 kg/m. The amniotic fluid, which is 99% water and therefore incompressible, was assumed to have a negligible Young's modulus and a Poisson's ratio of 0.49. The Young's modulus of 20 kPa is used for the fluid because moduli of lower values produced unstable results. The computational model uses peak von Mises strain in the uterus, near the placenta, as the measure for predicting risk of injury. High risk is associated with the presumed 60% strain tissue limit allowing the prediction of fetal injury based on the strain.

Material properties of the ligaments connecting the uterus to the pelvis were not available in the literature. A brief search of general ligament properties showed that the elastic modulus of ligaments is typically two orders of magnitude greater then the uterus [8, 24, & 25]. Therefore, the elastic modulus of the uterosacral and round ligaments is set to 100 times the modulus of the uterus. The density and Poisson's ratio were also taken from general ligament data [8 & 25]. An isotropic representation of fatty tissue has been used by Todd and Thacker [21] in modeling of the human buttocks. The Young's modulus for a seated female is 47 kPa with a Poisson's ratio of 0.49. This Poisson's ratio represents a nearly incompressible material. Contacts were created such that the fluid interior of the uterus was free to move within the uterus, with contact friction. However, the fluid could not penetrate the uterus or placenta. Default master/slave contact treatments within MADYMO were used for all contacts.

Four techniques were used to validate the pregnant model. First, a global biofidelity response was evaluated by using a seatbelt to compress dynamically the pregnant abdomen [17]. The force versus compression results were within the published corridors from scaled cadaver tests [7]. Second, a similar validation procedure was performed with a rigid bar [17] and these results were also consistent with previous data [7]. The third technique involved validating the model against real-world crashes in order to investigate the model's ability to predict injury. Using fatal crashes from pregnant occupants [11], the model showed strong correlation (R2 = 0.85) between peak strain at the uterine-placental interface (UPI) as measured in the model compared to risk of fetal demise as reported in the real-world crashes over a range of impact velocities and restraint conditions [14]. The forth method compared the physiological failure strain from placental tissue tests to the failure strain measured in the model. Tissue tests by Rupp et al. [20] suggested approximately a 60% failure strain for UPI tissues which is in agreement with the model's prediction of 75 % risk of fetal loss at a 60% strain in the UPI. In summary, the global, injury, and tissue level validation techniques all indicate the model is good at predicting injurious events for the pregnant occupant.

The current simulations were chosen to determine the effect of restraint use and occupant position on the response of the pregnant occupant. The test matrix consisted of 17 simulations in two groups. The first group of 15 simulations was performed with occupant position and occupant restraint variations (Table 1). The applied sled pulse is a half-sine wave imposed for duration of 100 ms. Acceleration is defined with respect to time; therefore the area under the curve corresponds to the change of velocity of the crash. Two interiors were used in the simulations; a standard driver-side interior and a passenger-side interior. The driver interior is a typical MADYMO interior made up of rigid planes to represent the seat, vehicle floor, and knee bolster. Positioning of the pregnant occupant was based on the seated anthropometry of a pregnant woman in her 30th week of pregnancy as defined by Klinich [10]. Four parameters were chosen to define the position of the occupant, using the parameter values that correspond to the small female group in the Klinich study (average height: 5 ft, average weight: 134 lb). The abdominal clearance, defined as the distance between the abdomen and the bottom of the steering wheel, is 38 mm. The mean overlap of the uterus to the steering wheel is 12%, where the overlap is defined as the ratio of the vertical height of the uterus above the bottom of the steering wheel to the total vertical height of the uterus. The seatback angle, relative to vertical, is 13 degrees, and the steering wheel tilt is 29 degrees from vertical. Standard MADYMO finite element belts are used for the three-point restraint condition. For the airbag tests, a MADYMO 600 mm driver airbag (volume = 35 L) is used, with inflation triggered 15 ms into the simulation.

The second group of two simulations was performed to explore the possibility of fetal brain injury due to inertial loading alone. In other words, these simulations were performed to investigate the possibility of fetal brain injury due to an acceleration rather than using the placental separation predictive measure as done in the previous 15 simulations. Therefore, two severe rear impact tests were performed using 100 ms pulse duration and 35 kph and 47 kph crash velocities. This direction was selected in order to generate a pure inertial load without interference from the belts or steering wheel. For these tests, the pelvis acceleration was recorded and a HIC value (15 ms) was determined. It was assumed that in the later part of gestation, the head of the fetus lies firmly in the cervix and is relatively fixed to the pelvis. Therefore, it is assumed that the pelvis acceleration acts as a marker for the fetal head acceleration; however, this assumption will estimate the upper bound of fetal head acceleration given that the coupling to the pelvis is not rigid.

RESULTS

For the pregnant driver occupant, the unrestrained occupant resulted in substantially higher risk of abdominal and head trauma compared to the fully restrained driver in a similar crash (Figure 3). For all simulations both strain in the uterus and maternal responses were considered with respect to fetal outcome (Table 1). Simulations in which the occupant was positioned in the passenger-side interior resulted in lower peak uterine strains measured at the uterine placental interface (UPI) compared to the driver-side interior for all restraints tested. Substantial reductions were seen for the unrestrained and 3-pt belt cases for similar crash speeds. For belted simulations, the peak strain is 26% to 36% less in passenger-side simulations compared to driver-side simulations even though the forward motion of the occupant is roughly equal between simulations with the same restraint. The key difference in the tests is the presence or absence of the steering wheel. In the driver-side configuration, the occupant contacts the steering wheel to some degree in all the configurations tested. A lower peak strain is recorded in the unrestrained cases because the abdomen does not contact the steering wheel, due to the seatbelts in the belted cases and due to the contact between the head and the windshield in the unrestrained case. For the two belted cases, the occupant does not approach the dashboard and therefore, strain is primarily due to inertial effects. The main effect of varying the occupant position, therefore, appears to be to alter the abdominal loading pattern from one of contact in the driver-side cases to one of inertia in the passenger-side cases.

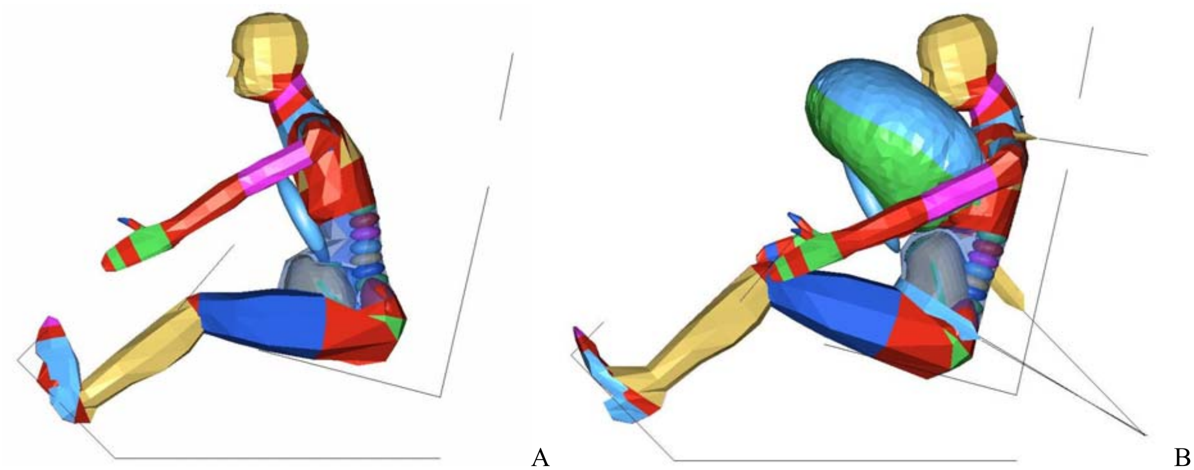


Figure 3. Unrestrained pregnant driver in a simulated 35kph crash (A), and full restrained at 35 kph crash (B).

Table 1.
Pregnant model test parameters and results.

Occupant	Restraint	Crash Speed (kph)	Risk of fetal death (%)	Maximum Strain in the Uterine Wall (%)	HIC	V*C (m/s)	Chest Deflection (mm)
Driver	None	13	44	23.3	1	0.12	38.6
Driver	None	20	65	36.6	13	0.31	39.1
Driver	None	25	77	44.6	41	0.47	39.4
Driver	None	35	100	60.8	156	0.72	39.7
Driver	3-pt Belt	13	32	15.5	4	0.03	43.4
Driver	3-pt Belt	25	51	27.9	62	0.09	47.1
Driver	3-pt Belt	35	89	52.6	185	0.12	52.4
Driver	3-pt Belt	45	99	58.7	211	0.13	54.3
Driver	3-pt Belt	55	100	61.2	310	0.17	58.2
Driver	3-pt Belt + Airbag	25	52	28.1	49	0.22	45.1
Driver	3-pt Belt + Airbag	35	59	33.0	114	0.24	48.2
Driver	3-pt Belt + Airbag	45	80	46.6	173	0.20	49.0
Passenger	None	35	52	28.2	2820	0.33	32.7
Passenger	3-pt Belt	35	60	33.7	181	0.30	51.5
Passenger	3-pt Belt + Airbag	35	46	24.4	140	0.27	47.8

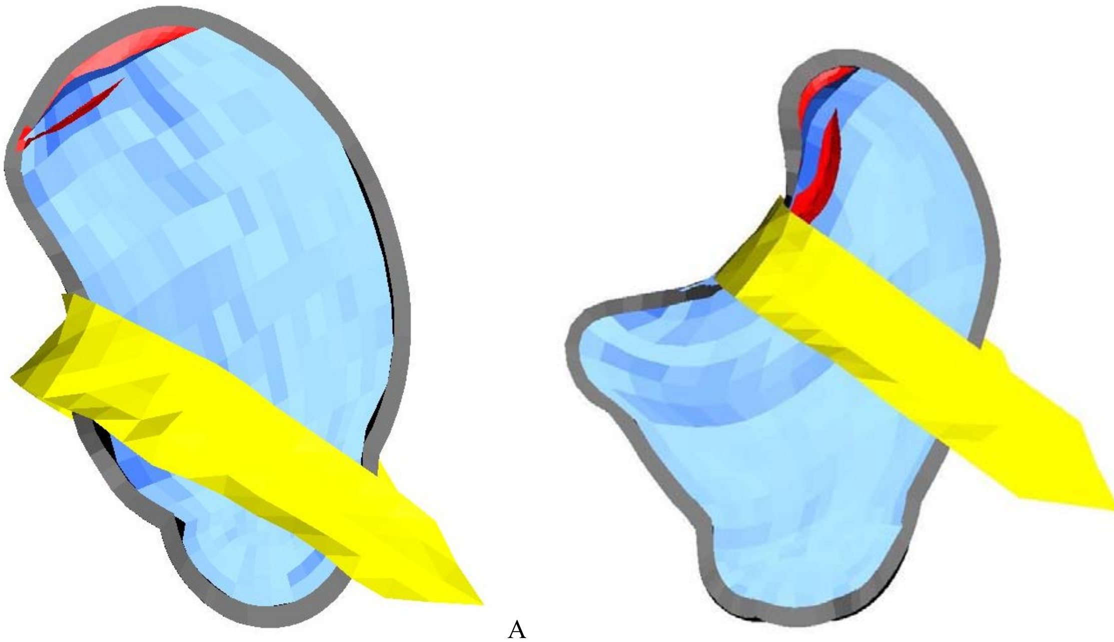
The importance of examining the maternal response is highlighted in the unrestrained passenger-side case. Although this simulation produced a low peak strain, based on the HIC value of 2820, it is reasonable to predict maternal death. This elevated value is the result of severe contact between the occupant's head and the dashboard. HIC scores for the remaining simulations were generally low and consistent between seating position. Thorax response for the unrestrained occupant shows the same trend as for the strain, where the limited contact between the thorax and any vehicle surface reduces the passenger injury risk as compared to the driver response. For the restrained occupant, a slight increase is seen in thorax injury risk with the removal of the steering wheel. This is a result of the contact between the steering wheel and the pregnant abdomen in driver-side simulations reducing the load applied to the shoulder belt as compared to the passenger-side.

In the second group of simulations, the seatback fully supported the occupant thereby resulting in the anticipated pure acceleration field presented to the pregnant abdomen. In the 35 kph crash simulation, the peak fetal head acceleration was estimated as a peak of 73.5 g with a 118 HIC. In the 47 kph crash simulation, the peak fetal head acceleration was 83.7 g with a 215 HIC.

DISCUSSION

Overall, there is a high probability that placental abruption would occur in the driver-side, unrestrained, frontal impact simulation. In the passenger–side simulation, there is a near 100% risk of life-threatening maternal brain injury in the similarly unrestrained condition, and therefore a high risk for fetal death. The use of a 3-pt. belt, as well as an airbag, reduces the risk to the pregnant women and the fetus. The difference in abdominal clearance between the driver-side and passenger-side simulations played an important role in peak strain in the uterine wall. The strain was 26% to 54% less in passenger side simulations, primarily due to the presence or absence of the steering wheel. Based on the results of this study it is recommended that, when practical, the pregnant woman ride in the passenger seat with a 3-point seatbelt and airbag with the seat positioned as far rearward as possible.

Placental abruption is believed to occur when the strain in the uterine wall exceeds 60%. The risk for placental abruption is largest for high strains that occur near the placenta which can be dramatically influenced by the lap belt position. Simulations have demonstrated that the vertical position of the lap-belt can increase fetal risk by a factor of three (Figure 4) [16]. As the lap-belt approaches the height of the placenta, which is located at the top of the uterus, the observed strain increases for a given crash pulse. Simulations with the lap-belt directly loading the uterus at the placental location, produced the highest recorded strain. Once the lap-belt height is above the placenta, the strain decreases with the strain for the top belt position matching that seen for the recommended belt location. However, it is important to note that there is increased risk to the mother with incorrect lap-belt placement, including elevated head and chest injury response. This is important because the best way to protect the fetus is to protect the mother.



A B

Figure 4. Simulations at 35 kph showing uterine compression for the correctly position belt (A), and the incorrectly positioned belt (B).

Predicting fetal injury from abdominal deflection is loosely analogous to using chest deflection to predict thoracic injury. As a simple comparison, chest deflection for the small female is limited to 52 mm by federal safety standards [4]. A chest deflection of 52 mm is approximately 35% compression which corresponds to approximately 40% risk of an AIS 3 or greater injury [12]. Given the obvious anatomical differences between the thorax and pregnant uterus, it is interesting that 35% compression of the uterus at is also the higher limit of injury [3]. The abdominal deflection could be measured in the same manner as chest deflection, using a string potentiometer, chestband, or through processing of digital video. It is important to note that the measurements need to be taken from a pregnant dummy with the correct anthropometry and abdominal force-deflection response as a pregnant woman.

When examining direct fetal head accelerations, the peak accelerations and HIC values are relatively high and justify additional concern. In order to put these values, which at first seem very low, into perspective, one can compare the 118 and 215 HIC values to the 390 HIC tolerance level for the 1 year old infant dummy [5]. Moreover, the fetal brain and vasculature is substantially less developed than even the 1 year old brain, and is much more likely to hemorrhage. Therefore, while the injury HIC values for a fetus are unknown, it is clear that they would be much less than the 1 year old.

Like most computer models used in automobile safety, this model of the pregnant female allows for the exploration of advanced restraint systems. For example, the original experimental research performed by King *et.al.* [9] Illustrated that a mesh webbing over the entire abdomen proved to be the best protective measure for the fetus. Therefore, a prototype belt was designed to mimic these properties and attach readily to the standard three-point seatbelt (Figure 5). The type of mesh and attachments can be optimized using this computer model. Moreover, other advanced restraint designs can be readily evaluated for potential risk to the fetus or pregnant occupant.

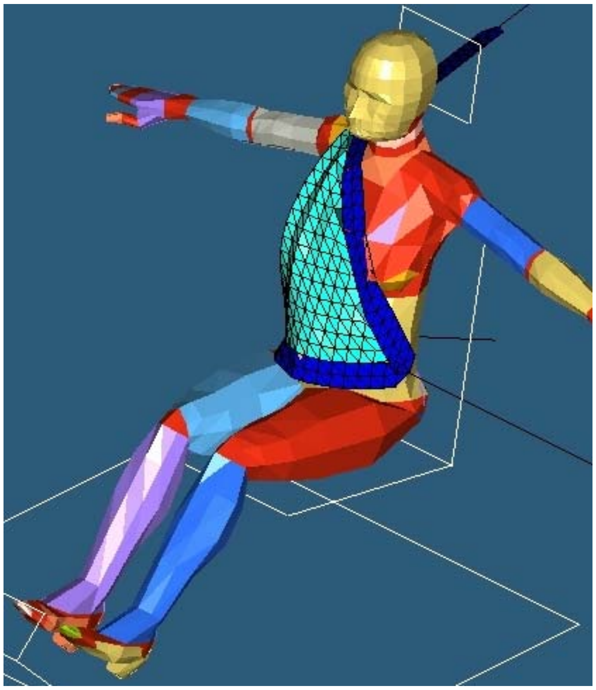


Figure 5. Advanced restraint for the pregnant occupant that can be added to a standard three-point belt.

It is important to note that previous simulations indicate that for all frontal impacts it is safest for the pregnant occupant to ride in the passenger seat while wearing a three-point belt and utilizing the frontal airbag when appropriate [16]. As with all computational models, this model is limited by the accuracy of input and simplifications made. The tissue data, from which the failure strain is derived, is sparse and simplifications are made to use that data as a material model. Additionally, the boundary conditions and geometry can and should be improved in future generations of the model. Furthermore, the model only looks at injury at the UPI. In cases with very large deflections, direct injury to the fetus may occur at injury rates different then those for placental abruption. It is recommended that the methods in this paper be applied to future generations of the pregnant occupant model to provide a continually improving understanding of pregnant occupant injury risk prediction.

CONCLUSIONS

A finite element model of the pregnant abdomen was created to predict fetal outcome following a motor vehicle crash. The model was incorporated into a human body model in a dynamic solver and validated with data from previous studies. The model is sensitive to changes in restraint conditions such as inertial, steering wheel, seatbelt, airbag, and combined loading. Peak uterine strain was reduced by 30% to 50% in passenger-side simulations vs. driver-side simulations, primarily due to increased distance between the abdomen and the nearest vehicle surface, namely the steering wheel for driver-side tests and the dashboard for passenger-side tests. Simulations results illustrated that the fetal brain may experience direct accelerations that are high enough to cause brain hemorrhaging, and therefore it is suggested that future computer models include the capability of quantifying fetal brain acceleration. Overall, the model has verified previous experimental findings regarding the importance of proper restraint use for the pregnant occupant. The model can be used to run quickly numerous tests and design advanced restraint systems specifically designed for pregnant occupants.

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